A Performance Comparison of Media Access Control Protocols for Vehicular Ad-hoc Networks (VANETs)

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ABSTRACT

The emergence of computationally rich vehicles and recent advances in wireless communication technologies are fueling vehicular network research in industry and academia. A key challenge to the successful deployment of vehicular communication is the implementation and efficiency of the Medium Access Control (MAC) layer. There are mainly two types of MAC approaches, namely contention-based and contention-free. The current standard, IEEE 802.11p, is a contention-based approach, which has the severe limitation of unbounded transmission delays. An alternative contention-free approach called Dedicated Multichannel MAC (DMMAC) has been proposed in the literature. In this work we analyze these two approaches, discuss their limitations and introduce an improved approach called Medium Access with Memory Bifurcation and Administration (MAMBA). We evaluate the performance of the three approaches in highway and urban scenarios, for both low and high density traffic. Our performance evaluation results show that MAMBA improves throughput and message delivery ratio by up to 150% and 205% over IEEE 802.11p and DMMAC approaches respectively. MAMBA also improves on the latency achieved by the other methods by up to 72% and 99% respectively, compared to IEEE 802.11p and DMMAC.

Keywords: Medium Access Control, Performance, Protocol, Throughput, Vehicular Ad-hoc Networks

1. INTRODUCTION

In the field of vehicular communications vehicles act as mobile nodes in wireless networks. In an ad-hoc network nodes communicate directly with each other, without an Access Point (AP). Vehicular Ad-hoc NETworks (VANETs) are different from other ad-hoc networks because of the high node mobility, the variable node density, and the unpredictable and harsh communications environment. To realize communications in a vehicular network, vehicles are equipped with On-Board Units (OBUs), and roads are equipped with Road Side Units (RSUs). An OBU aggregates data from the components in the vehicle, and has one or more radios built in to enable communications with OBUs in other vehicles and with RSUs. Communications between OBUs is called Vehicle-to-Vehicle (V2V) communications, and communications between an OBU and RSUs is called Vehicle-to-Infrastructure (V2I) communications. VANETs also form part of a larger effort, called Intelligent Transportation Systems (ITS), which aims to make transportation systems smarter, faster, safer, and more convenient. RSUs act as gateways to an ITS. The key components in a vehicular network, and how they interact, are indicated in Figure 1.

Research on VANET covers several areas which include: routing [1] [2] [3] [4], broadcasting [5] [6][46], security [7] [8][43][45][47], Quality of Service (QoS) [9] [10][44], standardization of vehicular protocols and technologies [11], support for applications [12], and Medium Access

Control (MAC) [13] [14] [15]. Vehicle-based communications finds application mainly in three areas, namely safety, traffic management, and infotainment [1] [16] [17]. Each of these application areas imposes different requirements on vehicular networks. Safety applications require latency guarantees, but low bandwidth. Traffic management applications typically require hierarchical communication structures with intelligent aggregation, but are more tolerant to delays [18]. Infotainment services have high bandwidth requirements, but losses are acceptable [13].

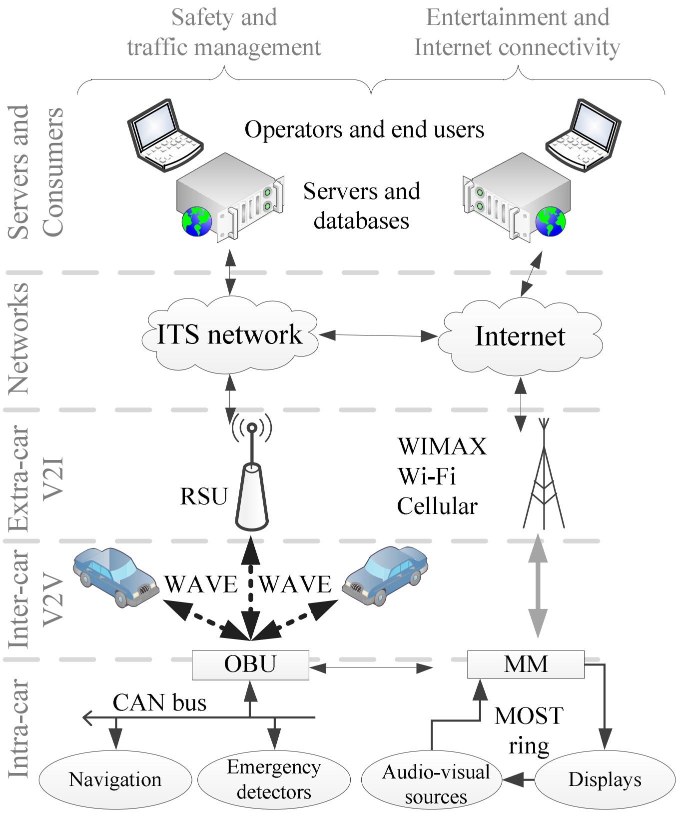
In this work, we focus on safety applications because this is viewed as the most valuable application for vehicular communications [19]. Consequently, these applications have received a lot of attention from researchers, designers, and application developers working in the VANET area. Examples of safety applications areas include change assist, intersection collision avoidance, and advance emergency notification.

MAC layer support is crucial for safety applications because it governs access to the wireless medium used for inter-vehicular communications, which have a direct impact on the performance of safety applications. Access to the underlying wireless medium is one of the dominant factors affecting efficient and reliable communications in any wireless network, and even more so in the vehicular environment where nodes are inherently mobile and the network topology continually changes. Many MAC approaches have been proposed for the vehicular environment recently [20] [9] [21] [22] [14] [15] [23].

1.1 Contributions of this Work

In this paper we present a performance comparison of different types of MAC approaches proposed for V2V communications [13]. In particular, we focus on three MAC methods: IEEE 802.11p, the proposed standard for medium access, standardized by the IEEE for Wireless Access for the Vehicular Environment (WAVE) [24], Dedicated Multi-channel MAC (DMMAC) [15], and our optimized version of the DMMAC protocol which henceforth is referred to as Medium Access with Memory Bifurcation and Administration (MAMBA) in the rest of the paper. We focus on these two approaches because they are representative of the fundamental conceptual divide in approaches to delivery of safety messages in V2V MAC design: the choice between contention-based and contention-free methods. IEEE WAVE is a contention-based MAC, while DMMAC uses a time-multiplexed combination of self-organizing contention-free and contention-based methods. We provide a detailed analysis of these two MAC approaches below.

Our performance evaluation tests are conducted using a network simulator, OMNeT++ [25], a road traffic simulator, Simulation of Urban MObility (SUMO) [26], and four representative traffic environments that include high density urban, low density urban, high density highway, and high density highway.



CAN	Controller Area Network	OBU	On Board Unit
ISP	Internet Service Provision	RSU	Road Side Unit (WAVE)
ITS	Intelligent Transportation Systems	V2I	Vehicle to Infrastructure
MM	MOST Master	V2V	Vehicle to vehicle
MOST	Media Oriented Systems Transport	Wi-Fi	Wireless Fidelity
WIMAX	Worldwide Interoperability for Microwave Access		
WAVE	Wireless Access in Vehicular Environments		

Figure 1: Generic architecture of a vehicular network.

The rest of this paper is organized as follows. In section 2 we describe related work undertaken in the MAC area for the vehicular environment. In section 3 we describe the shortcomings of the current IEEE 802.11p and DMMAC MAC approaches, and in section 4 we propose a new approach called Medium Access with Memory Bifurcation and Administration (MAMBA) that addresses these challenges. In section 5 we describe the simulation test bed used in our performance evaluation tests as well as the performance metrics used. We present our performance evaluation results of the MAC approaches (including MAMBA) in section 6. Finally, section 7 concludes the paper.

2. RELATED WORK ON MAC APPROACHES

In this section we present a short overview of recently proposed MAC approaches. A vehicular MAC plays a fundamental role in determining access (right of use) to the underlying wireless communication in vehicular environments. The vehicular environment presents various challenges for efficient and reliable communications; these are described in [1] and [27]. The main challenge for a vehicular MAC is the high mobility of vehicles and the unpredictable environment [14]. A comprehensive analysis of MAC approaches for the vehicular environment is given in [13]. The authors in [13] distinguish between vehicular MAC methods that are contention-based, contention-free, and a hybrid of these two. Contention-based approaches perform better under low traffic loads and contention-free approaches perform better under heavy load. The authors also describe the importance of the agent that coordinates medium access in a distributed network with high mobility such as vehicular networks. For contention-free MAC methods in distributed networks with high mobility, the coordinator is either an appointed or elected leader node, or the nodes self-organize to allocate time-slots.

2.1 IEEE WAVE MAC Standards (IEEE 802.11p, IEEE 1609.4)

The IEEE has standardized Wireless Access in the Vehicular Environment (WAVE) communications by introducing the IEEE 1609.1-4 [28] [29] [30] [31], and the IEEE 802.11p [15] standards. Figure 2 illustrates how these standards relate to each other. IEEE 1609.4 enhances the IEEE 802.11p (which specifies the PHYsical (PHY) and MAC layers) by supporting the multi-channel operation.

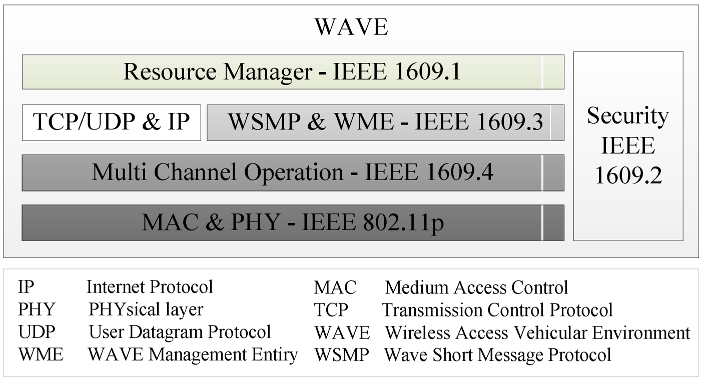


Figure 2: IEEE standards applicable to WAVE communication.

The PHY of IEEE 802.11p is based on IEEE 802.11a, which uses Orthogonal Frequency Division Multiplexing (OFDM). WAVE allocates 75 MHz in the 5.9 GHz region to seven channels. One channel is designated as a Control CHannel (CCH) for emergency and coordination, four channels as Service CHannels (SCHs), and a channel each for critical messages and high power public safety messages. The channel numbers, associated frequencies, and channel labels are shown in Table 1.

Table 1: WAVE Channel allocation [32].

Frequency (GHz)	**Designation**	**Channel label**
5.860	Critical, safety of life	SCH
5.870	Service channel	SCH
5.880	Service channel	SCH
5.890	Control channel	CCH
5.900	Service channel	SCH
5.910	Service channel	SCH
5.920	High power, public safety	SCH

Henceforth, we will refer to the CCH as Channel 1 and the remainder as Channels 2 through 7. The IEEE 1609.4 standard specifies the channel synchronization scheme, which contains a repeating 100 ms synchronization interval that is divided between 50 milliseconds (ms) CCH Intervals (CCHI) and 50 ms SCH Intervals (SCHI), as illustrated in Figure 3. During the CCHI all nodes tune to the CCH to listen for emergency messages and advertisements of services on other channels. If a node is interested in the service or information on an SCH channel, it tunes to that channel during the SCHI. Transmission in the six SCHs occurs concurrently during the SCHI. Services are typically provided by RSUs. Synchronization is performed on every Universal Time Coordinated (UTC) second and is achieved through GPS reception. The synchronization scheme also accommodates guard bands for radio switching times.

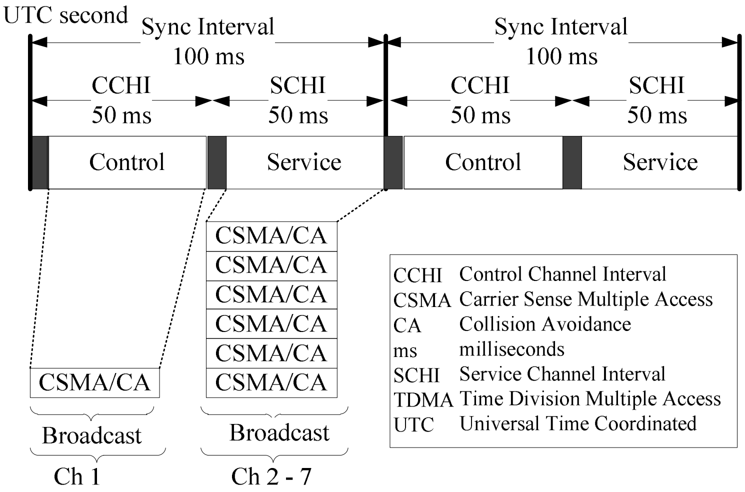


Figure 3: Message structure of IEEE 802.11p.

The emergency messages, advertisements, and actual services in both the CCHI and the SCHI, are broadcast to all nodes as intended recipients. All nodes within the range of the transmitter are eligible to receive a message.

The basic MAC technique used by 802.11 is the Distributed Coordination Function (DCF). We describe DCF for the *broadcasting* mode [32]. When a node has a packet to transmit, it senses the medium until it detects an idle state (i.e. no transmissions) for a period called the DCF Inter-Frame Space (DIFS). After sensing such a period of inactivity on the medium, the node selects a counter value for an additional waiting period called the Contention Window (CW). The counter value is selected randomly, but within bounds of a set minimum and maximum called CWMIN and CWMAX. While the medium is idle, the CW counter counts down until it either reaches zero or senses activity on the medium. If it senses activity on the medium, the count-down on the CW counter is paused, until the medium is idle for a period of DIFS again. When the counter reaches zero the node transmits the packet. The sequence is illustrated in Figure 4.

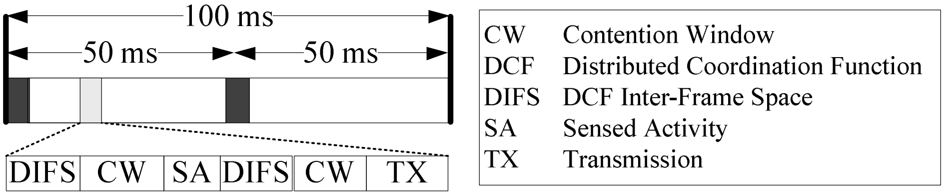


Figure 4: IEEE 802.11 Distributed Coordination Function (DCF) in the broadcasting mode.

The contention-based MAC approach used in the IEEE 802.11p standard is the Enhanced Distributed Channel Access (EDCA), as defined by IEEE 802.11e [33]. EDCA is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). EDCA improves Quality of Service (QoS) by providing different message priorities. Prioritization is achieved by varying the

Contention Windows (CWs) and the Inter-Frame Spaces (IFS), which changes the probability of successful medium access.

2.2 Dedicated Multi-channel MAC (DMMAC)

In [15], Lu et al. proposed an alternative MAC approach (called DMMAC) to the WAVE standards. DMMAC is chosen primarily because it is based on WAVE, but in contrast to WAVE, it uses contention-free medium access for safety message transmissions in the CCHI. The authors keep the synchronization structure of IEEE 1609.4, but the CSMA/CA scheme from IEEE 802.11p is replaced by a complex combination of Time Division Multiple Access (TDMA) and CSMA/CA illustrated in Figure 5.

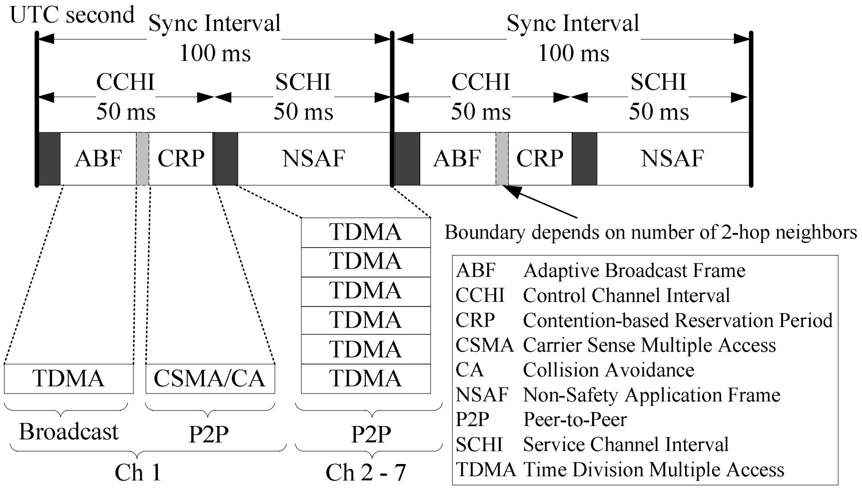


Figure 5: Message structure of DMMAC.

The CCHI is split into an Adaptive Broadcast Frame (ABF) and a Contention-based Reservation Period (CRP). The SCHI is dedicated to non-safety transmissions that make up the Non-Safety Application Frame (NSAF). The boundary between the ABF and the CRP is flexible and adapts to accommodate the number of nodes within range. The CRP is used to contend for a time slot and a channel for non-safety communications in the NSAF. The contention during the CRP is based on a three-way handshake between two nodes, i.e. using ad-hoc Peer-to-Peer (P2P) transmission. During the handshake, which is made up of a request, response and an acknowledgement, the two nodes agree on a slot and a channel for a data exchange in the SCHI. The authors describe in detail the ABF, which is the focus of the work in [15], and also the focus of our work in this paper. The ABF is used to broadcast safety messages and other control messages, akin to the CCH in WAVE. The difference between the WAVE CCH and the ABF is that the transmissions in the ABF are contention-free because of the self-organizing TDMA. To realize this self-organizing TDMA, which is needed for nodes to have contention-free broadcasts in the ABF, slots of 1 ms each are made available for nodes to allocate for themselves. During every allocated (owned) slot, the node that owns the slot transmits what is called an Information Frame (IF). The IF contains the transmitting node's IDentification number (ID), some information to allow neighbor nodes to calculate the boundary between the ABF and CRP, followed by the complete Slot Allocation Table (SAT) according to the transmitting node. The SAT is different from the bitmap used in methods such as [20], since the occupying node's ID is also communicated. The structure of the ABF is shown in Figure 6.

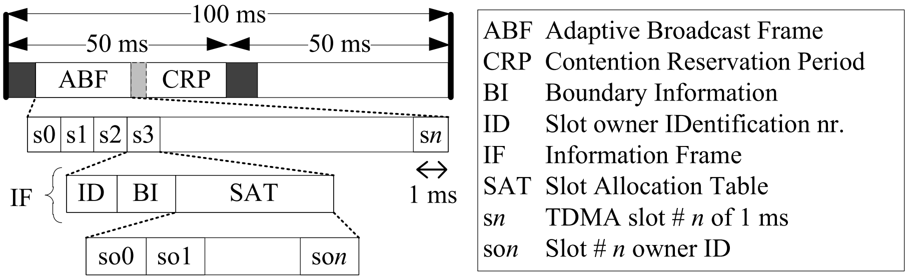


Figure 6: Structure of the ABF used in DMMA.

In this paper we focus on the transmission of safety and other control messages in the ABFs. To enable us to objectively and fairly compare the ABF section of DMMAC with the CCH of WAVE's IEEE 802.11p standard, we will assume the length of the ABF is fixed at 50 ms, i.e. zero CRP, resulting in 50 slots of 1 ms each. We describe below the slot allocation, transmission, and reception processes for the ABF, as presented in [15], using the flow diagrams shown in Figure 7.

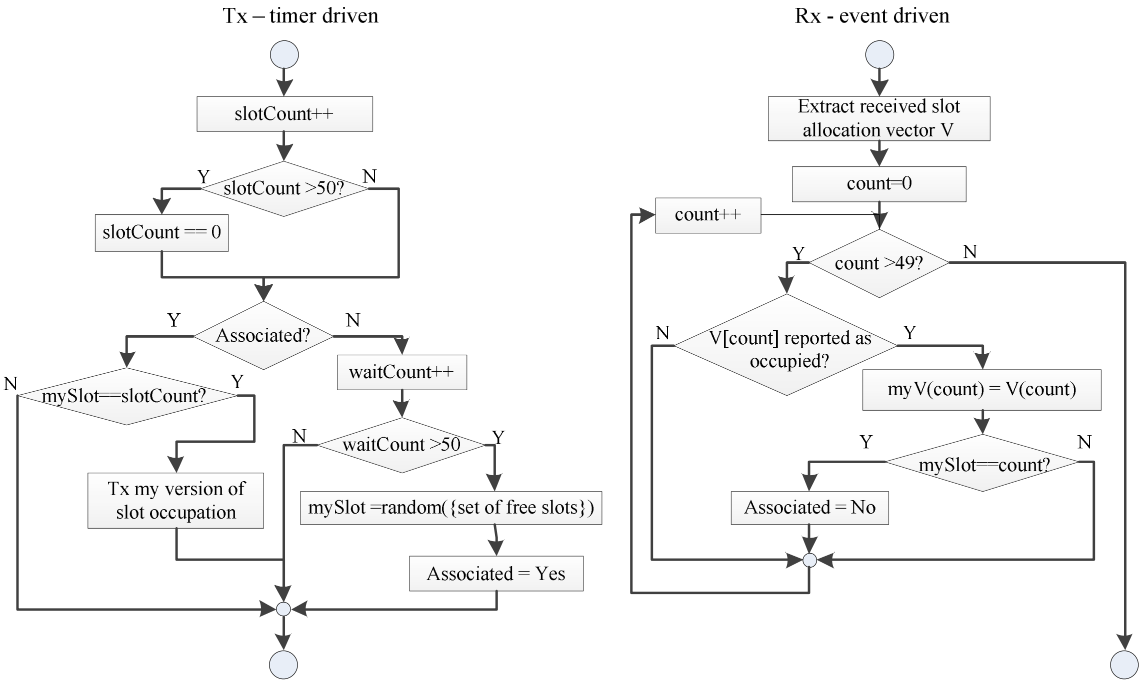


Figure 7: Flow charts for the self-organizing TDMA used in DMMAC adapted from [15].

The transmission routine (Tx) is started by a timer that is triggered once every 1ms. The receive routine (Rx) is triggered by a receive event from the physical layer. Every node transmits its own perception of slot allocation to all other nodes, with its communication payload, when it is its turn to broadcast. There is continual learning taking place as each node's slot allocation perception is updated based on the information it receives from its neighbors within range. All nodes are therefore informed of the slot allocation perceptions of their one-hop neighbors. After power-up, a node listens for at least a full cycle (100 ms) to the transmissions from all the nodes within range. If there are *n* vehicles in range, it receives *n* reports on the allocation of 50 slots. The node can therefore determine which slots are unoccupied and can attempt to occupy one of the available slots. The node selects one of the available slots at random and in the following cycle attempts to transmit during that slot. If at any stage any other node reports the selected slot is occupied by another node, or if any node reports the selected slot as unoccupied subsequent to the first transmission, the node surrenders its slot and enters the slot selection process again. The rationale is that, if one node is within range of another node, communication should work both ways. Therefore, any other node that reports this node's slot as empty had other interference during this node's transmission and therefore the slot is not suitable.

3. LIMITATIONS OF IEEE 802.11P AND DMMAC

In this section we highlight the limitations of the IEEE 802.11p and DMMAC approaches.

3.1 Limitations with the IEEE 802.11p MAC

As we mentioned in the previous section, IEEE 802.11p is contention-based. Contention-based MAC methods cannot provide a bound on access delays, which is critical for safety message delivery [20].

3.2 Limitations of DMMAC

The work in [15] describes the ABF used in DMMAC and how the boundary between the ABF and the CRP is achieved. In this work we focus on the rules that govern and coordinate contention-free access to the wireless medium during the ABF. In this section we identify weaknesses in the ABF described in [15]. These weaknesses were not revealed in the results reported on in [15] because of the very basic vehicular scenario used for simulation. The simulation in [15] was limited to a straight highway scenario involving only 30 vehicles, which means the slots would probably not have saturated. The vehicles start with 150 m separation and an initial speed of 30 m/s, and then progress to a dense scenario where the separation is 10 m. This basic model does not take into account lane changes, overtaking, introduction of new vehicles, and termination of vehicles, and bidirectional traffic.

3.2.1 SAT propagation through n-hop neighbors

The ABF procedure described in [15] states that every node listens to its neighbors to determine slot allocation of all its neighbors within 1-hop distance. However, the approach does not take into account that the information in the SAT is distributed far beyond the 1-hop periphery. As an example, take the four nodes in Figure 8 with a 4-slot SAT. Starting with an empty SAT, node A will occupy an unused slot (slot 1), and node B will receive the notification. Node B will occupy an unused slot (slot 3) and nodes A and C will receive notification from node B, indicating slots 1 and 3 are used by nodes A and B respectively. Node C will update its own SAT with this information and occupies a free slot (slot 2). It will then notify node D that slots 1, 2 and 3 are occupied by nodes A, C and B respectively. When node D selects the only remaining free slot (slot 0), it notifies node C, which notifies node B, which in turn notifies node A. Any subsequent nodes that come within the range of **any** of these nodes will deduce that there are no available slots.

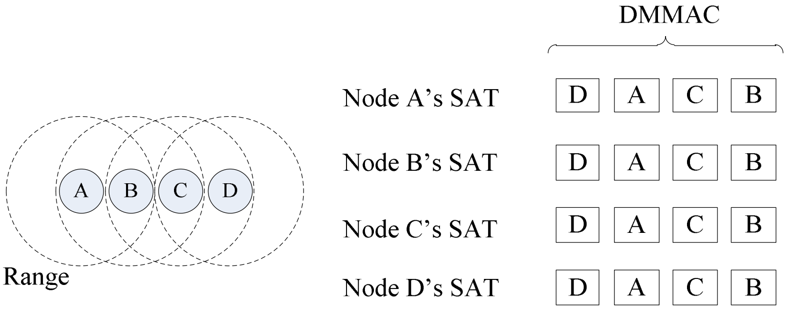
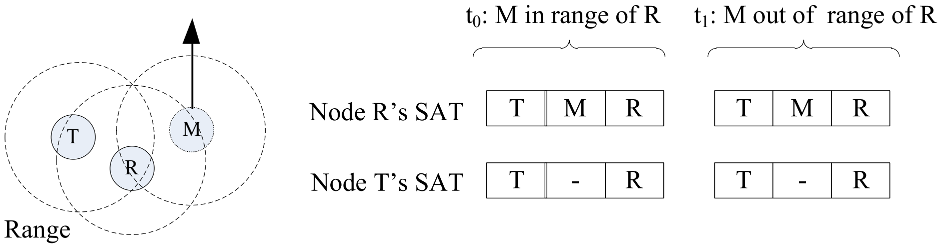


Figure 8: Saturated steady-state SATs for DMMAC.

3.2.2 Collective additive system memory

The method described in [15] requires that every node uses its self-allocated slot to transmit. With every transmission the node sends its version of the Slot Allocation Table (SAT). Upon reception of a message the receiving node interprets the received SAT and updates its own version of the SAT by appending slot allocations reported by neighbors. The addition is therefore based on information from a single node. The receiving node cannot, however, remove slot allocations based on information from a single node because a third node may be, or may have been, within the range of the receiving node, but out of the range of the transmitting node as indicated in Figure 9.



T: Transmitting node R: Receiving node M: Transient mobile node

Figure 9: Node R cannot depend on node T's Slot Allocation Table to remove node M from its own Slot Allocation Table.

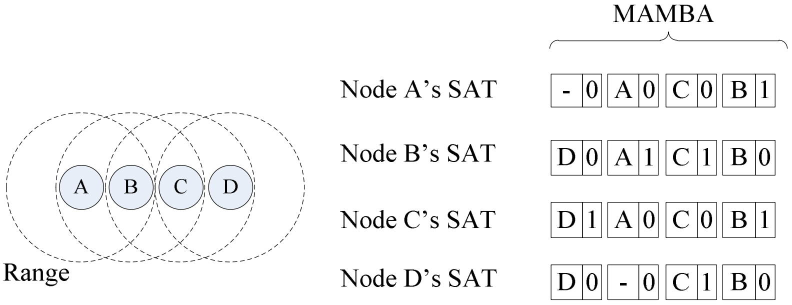
The effect of other nodes' SAT is therefore additive or substitutive, but taken in isolation (i.e., two nodes at a time), it cannot be subtractive. Every node therefore continually appends the ID numbers of transmitters to its local SAT, which steadily fills up as new nodes occupying slots are reported. Although the method is cumulative, nodes can replace one another in the SAT because the receiving node just takes the ID of the last reported transmitter for a given slot. This method is problematic because the SAT becomes saturated and nodes will be unable to occupy a slot.

4. MEDIUM ACCESS WITH MEMORY BIFURCATION AND ADMINISTRATION (MAMBA)

In this section we described MAMBA by introducing two key improvements to the DMMAC approach.

4.1 SAT propagation through n-hop neighbors

To address the problem with the slot information propagating beyond the 1-hop neighbors, we modified the protocol by adding an extra bit to every slot in the SAT. This bit indicates whether the node number in the relevant slot (indicating which node occupies the slot) was reported by the occupying node itself (i.e., the node transmitting the SAT heard it first hand), or whether it was received from another node. The receiver sets this bit for a slot in its own SAT when a transmitting node reports that a slot is occupied by itself, i.e. a node with the same ID as the transmitting node. Using this information, a receiving node can easily distinguish between an immediate neighbor in range (a 1-hop neighbor) and one that is further away. In our proposed MAMBA approach, a receiving node only adds slots owned by 1-hop neighbors and immediate neighbors to its local SAT, thereby preserving slots that would otherwise have been consumed by nodes that are beyond the transmission range of the receiving node's 1-hop neighbors. Figure 10 shows how the modification makes an additional slot available for nodes in the range of only node A and nodes in the range of only node D.



Node A's SAT	-	0	A	0	C	0	B	1
Node B's SAT	D	0	A	1	C	1	B	0
Node C's SAT	D	1	A	0	C	0	B	1
Node D's SAT	D	0	-	0	C	1	B	0

Figure 10: Saturated steady state SATs for improved DMMAC.

4.2 Collective system memory

To resolve the problem with the SAT saturating due to the additive nature of the collective system memory, we modify each node to perform an additional check across all reported SATs after every ABF. We modified the receiving functionality to keep track of how many times a slot is reported as occupied (only by its 1-hop and immediate neighbors) during the complete ABF of 50 ms. If none of the 1-hop and immediate neighbors report the slot as occupied, the slot in the SAT is cleared. This means a node bases its decision to delete a node from its SAT not only on a single mode's information but also on the collective slot occupation information received from all immediate and 1-hop neighbors. This modification does not affect the information that is transmitted, only the way it is interpreted by the receiver, and therefore no additional packet overhead is required for the improvement. This modification does, however, require additional processing and storage at the receiving node. In Figure 11 node R's SAT obtains an additional free slot because of this improvement.

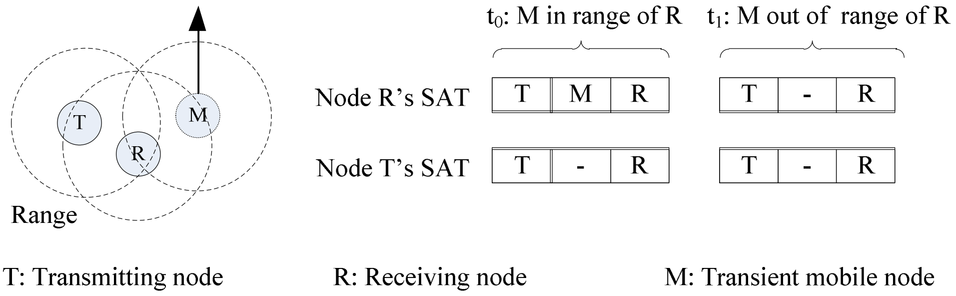


Figure 11: Node R removes M from its SAT based on the improvement.

5. SIMULATION TESTBED

In this section we describe the simulation setup used in our performance evaluation tests. The setup includes a network simulator, a road traffic simulator, and real-world maps. The OMNeT++ network simulator is used with the MiXiM framework. OMNeT++ is a modular network simulation framework that uses components written in C++ [25]. MiXiM is an extension to OMNeT++ that provides a simulation environment for mobile wireless networks [34]. To ensure that the traffic is representative of real-world traffic for each of the test cases, we used real-world maps from [35] and a road traffic simulation package, called Simulation of Urban MObility (SUMO) [26].

We conducted performance evaluation tests for both urban and highway driving scenarios and for each, we also performed experiments for both heavy and light vehicle traffic loads to investigate the scalability of the various MAC methods. To generate realistic results, it is imperative that both the network simulator and road traffic simulator are set up to use realistic and representative parameters [21]. We also describe the various performance metrics and the parameters used in our simulation tests. The rationale for the values assigned to the various simulation parameters is also given.

One of the problems associated with many of the proposed vehicular MAC methods is the representativeness of the simulated vehicular scenarios, as evidenced by the works in [13], [36], [37] and [38]. To accurately simulate communications in a vehicular environment, both the movement of vehicles and communications properties need to be taken into account [39]. The works in [14], [15], [9], [20] and [10] use limited sets of traffic scenarios, for example by only evaluating a straight piece of highway with all vehicles traveling at constant speed or the traffic scenario does not take lane changes into account. Some use proprietary network simulations that do not take into account all the network simulation parameters to evaluate the proposed MAC methods. These parameters include signal attenuation and fading, radio switching times, receiver sensitivity, transmitter power, etc. The work in [14], for example, uses a single range value to represent the wireless simulation parameters. If the separation between nodes is less than a range the assumption is made that the packet is successfully transmitted.

Table 2 lists the parameters used for our traffic simulation tests. Table 3 lists some of the network parameters used in our network simulation tests.

Table 2: Parameters used for our vehicle simulation tests.

Parameter	Value
Highway	For the highway scenario we used an average traffic load of 12 vehicles/lane/km for low density traffic, and 24 vehicles/lane/km for high density traffic [39]. The highway is a 1.765 km section, downloaded from OpenStreetMap [35] with three

	lanes in each direction. The length allows for averages of 125 active vehicles and 250 active vehicles in the low traffic density and high density scenarios respectively.[1] The simulator randomly selects from which lane a vehicle departs on the highway. The vehicles are instructed to follow the highway speed limit, to a maximum of 35 m/s for a third, 28 m/s for a third and 20 m/s for a third of all vehicles.
Urban Area	For the urban scenario, we used an average traffic load of 50 vehicles/km^2 for low density traffic, and 100 vehicles/km^2 for high density traffic [39]. The urban area is a 3 km^2 urban area, downloaded from OpenStreetMap [35], with single-lane roads, multi-lane roads, 4-way crossings with stop signs and 4 way crossings with traffic lights. The area allows for averages of 150 active vehicles and 300 active vehicles in the low density traffic the high density traffic scenarios respectively.[1] Vehicles are instructed to complete randomly generated routes through the area.

Table 3: Simulation parameters used in our simulation tests

Parameter	**Value**	**Unit**	**Source**
Carrier frequency	5.9	MHz	Specified in [24].
Maximum transmit power	100.0 (20)	mW (dBm)	Class C device specified in [24] and [40].
Bitrate	10	Mbps	As per [15]. In range of bit rates specified in [24] (3 – 27 Mbps).
Packet size	8	kbits	In range of maximum packet size specified in [24] and [30] (1.4 kB = 11.2 kbits).
Path loss factor (α)	3	-	[41]
Receiver sensitivity	-80	dBm	[40] This power was used for all the MAC methods in this work to ensure fair comparisons.
CWMIN, CWMAX	31,1023	-	Specified in [24]. Used for IEEE 802.11p only.
Simulation time	200	seconds	This was determined empirically. Given a stable flow (entrance and departure) of vehicles, the network stabilizes after about 80 seconds, which leaves120 seconds to evaluate the steady-state behavior.

Table 4 lists some of the performance metrics used when evaluating MAC methods in the vehicular environment [20] [9] [21] [22] [14] [15] [23]. These metrics can be applied to a single node, or the whole network of vehicles.

Table 4: Common performance metrics used for evaluating MAC methods.

Performance Metric	**Description of Performance Metric**
Medium access delay	Maximum time to wait to access the medium from the application layer, to the PHY layer, through the MAC layer.
Latency	Time it takes to send data between two points in the network, measured from the application layer of the transmitting node, to the application layer of the receiving node.
Network throughput	Measures the data transmitted and received in a given time.
Overhead	Ratio of application layer throughput to physical layer throughput.
Fairness	The fairness metric depends on a subjective definition thereof. In [21], a fairness index measures the likelihood for each node to transmit relative to its speed.

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[1] The total number of vehicles in the simulation is much higher than the number of active vehicles at any given time, since cars appear at the base and disappear at the end of the highway.

Message delivery ratio	The ratio of number of messages successfully delivered to the number of messages transmitted.
Network stabilization time	Time it takes for all nodes to be allocated a transmission slot and for the network to reach a stable state.

As mentioned previously in this work, we focus on broadcasting safety and control messages during the CCHI. We use the message delivery ratio and the network throughput performance metrics to measure and compare the efficiency of the MAC methods.

The throughput γ is defined as

$$\gamma = \frac{\sum_{i=1}^{N} \rho_i}{t\bar{N}} \tag{1}$$

and the message delivery ratio r is defined as

$$r = \frac{1}{\bar{\theta}\bar{N}} \times \frac{\sum_{i=1}^{N} \rho_i}{\sum_{i=1}^{N} \tau_i} \times 100\% \tag{2}$$

where $\bar{N}$ is the average number of active nodes (vehicles) in the network, t is the sample duration, ρ_i is the number of packets received by node i, and $\boldsymbol{\tau_i}$ is the number of packets transmitted by node i. In the highway scenarios $\bar{\theta}$ is the ratio of a radio's communication range to the highway length, and in the urban scenario it is the ratio of the surface area of a radio's range to the network surface area. The term $\bar{\theta}\bar{N}$ therefore approximates the number of vehicles in contact with a transmitting node at any given time.

6. PERFORMANCE ANALYSIS OF MAC APPROACHES

In this section we present the simulation results obtained with the IEEE 802.11p MAC, DMMAC and MAMBA approaches.

The network throughput, as defined in equation 1, is shown in Figure 12 for the three MAC methods in each of the four traffic scenarios described earlier. The results in Figure 12 show that in all scenarios, MAMBA significantly outperforms the other MAC methods.

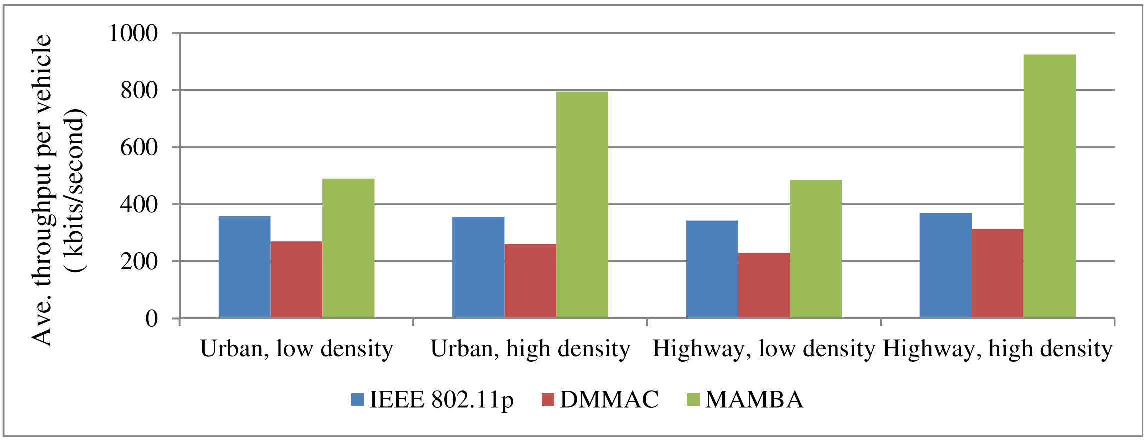

Figure 12: Throughput (data delivered in the network per vehicle per second) achieved for MAC methods for each scenario.

Table 5 gives a summary of the percentage improvements achieved with MAMBA over the other MAC methods in each scenario. It can be seen that the performance improves between 37% and 110% for the low density scenarios and improvements of 123% to 205% are obtained with the high density scenarios. The performance improvements in terms of throughput and message delivery ratio are the same, since the vehicular parameters and the number of packets generated are the same for a given scenario. Hence all the factors in equation 1, except number of packets received, cancel out when relatively compared.

Table 5 Percentage improvement (both throughput and message delivery ratio) of MAMBA over IEEE 802.11p and DMMAC for given scenarios

	Percentage Improvement of MAMBA over IEEE 802.11p	**Percentage Improvement of MAMBA over DMMAC**
Highway, high density	150 %	195 %
Highway, low density	41 %	110 %
Urban, high density	123 %	205 %
Urban, low density	37 %	82 %

The reason for the poor performance of IEEE 802.11p relative to MAMBA is due to the contention-based approach of IEEE 802.11p. Since nodes have to contend for the medium, a lot of time is spent waiting for the DIFS and CW periods to complete. The improvement over IEEE 802.11p is higher in the high density scenarios because, as expected, the contention-based IEEE 802.11p degrades in performance as the load increases.

The reason for the poor performance of DMMAC relative to MAMBA seems to stem from the wastage attributable to the number of times a node was unable to allocate any of the ABF slots. The lack of available slots is due to hearsay status of information that is propagated with this MAC approach. With MAMBA the nodes continually refresh their SATs, and ignore slot information that originates from beyond the 1-hop neighbors. It never happens during the simulations that a node cannot allocate a slot for MAMBA, as shown in Table 6.

Table 6: Number of times a node was unable to find an available slot during the simulation, expressed as a percentage of transmission attempts in the network.

	DMMAC
Urban, low density	5.36%
Urban, high density	7.97%
Highway, low density	6.25%
Highway, high density	7.25%

Figure 13 shows the message delivery ratio (as defined in equation 2), for the MAC methods under the different traffic scenarios. The results show a similar trend to that in Figure12, except for the effect observed caused by the number of vehicles.

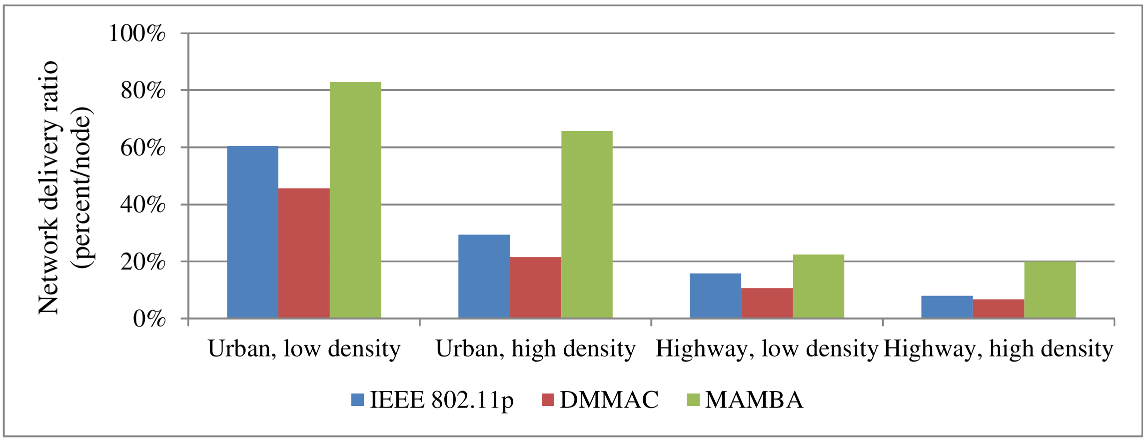

Figure 13: Message delivery ratio (equation 2) achieved for MAC methods for each scenario

Figure 14 shows how the MAC methods perform in the different scenarios over time. It can be seen from the results shown in Figure 14 that, except for the first 50 seconds in the low density scenarios, MAMBA steadily, and by a large margin, outperforms the other MAC approaches. During the first 50 seconds the vehicle density is relatively low while the roads are being populated with vehicles, which results in the contention-based IEEE 802.11p performing well and the DMMAC method's limitations not being reached yet. Figure 14 also shows that, for the highway scenarios, the DMMAC method initially performs well compared to the IEEE 802.11p, but starts to suffer after about 60 seconds due to the SATs becoming saturated as a result of the problems described earlier. In addition, it is interesting to note that the DMMAC performance seems to oscillate in the two highway scenarios. This behavior is due the way the SATs are maintained in DMMAC: The SATs are not cleared, as is the case with MAMBA, but overwritten when vehicles or groups of vehicles come into contact with each other and have to resolve slot allocation conflicts. The performance degradation cycle occurs when the SATs saturate and the improvement cycle is apparent when the SATs re-organize themselves during conflict resolution with either oncoming traffic or fast platoons catching up with slower ones.

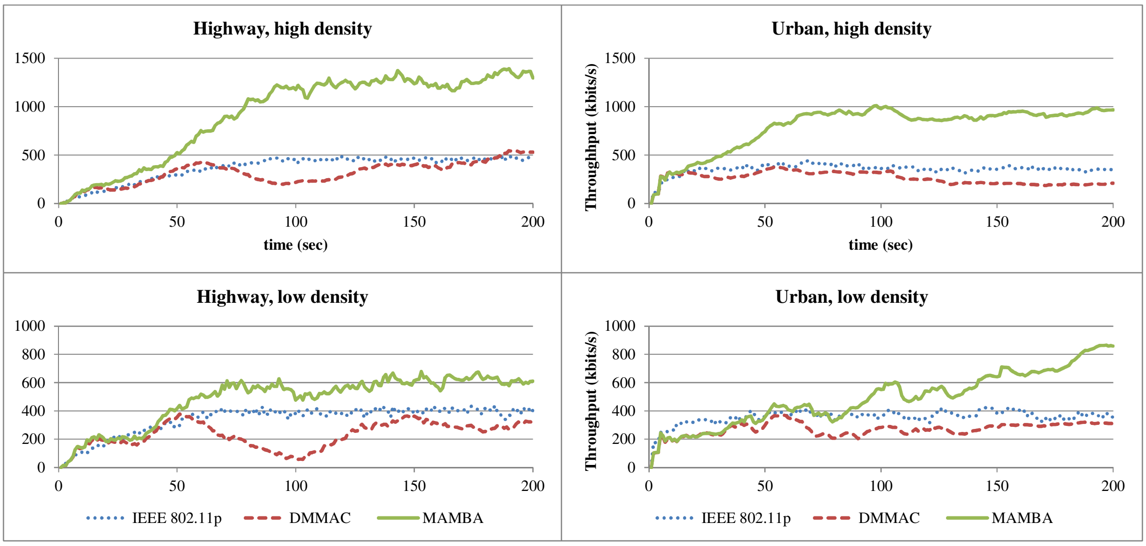

Figure 14: Throughput (data delivered in the network per vehicle per second) comparison

The latencies of transmissions using each of the MAC methods in the four traffic scenarios are shown in Figure 15. The median values are shown for the whole network and based on a sample of 20 seconds, from 80 seconds to 100 seconds. This time segment was chosen to allow the network to reach steady state.

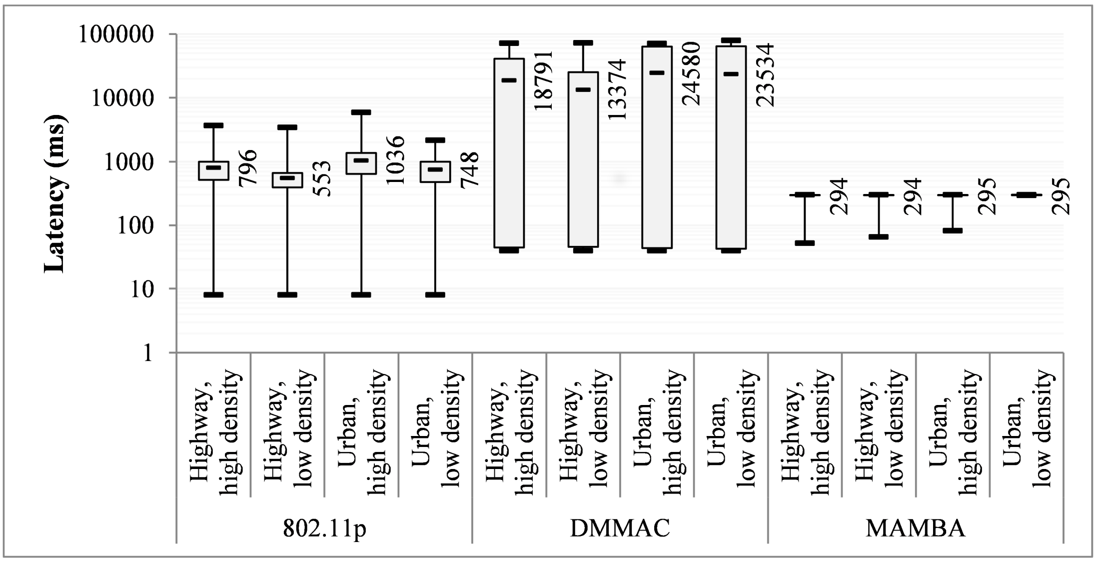

Figure 15 Latency (measured from transmitting application layer to receiving application layer).

The results in Figure 15 show that the MAMBA improves on the median results achieved by IEEE 802.11p and DMMAC in all the scenarios. MAMBA also improves on the maximum values seen during the sampled period. The improvements, expressed as a reduction in median latency, are given in Table 7.

Table 7 Percentage improvement (expressed as median latency reduction) of MAMBA over IEEE 802.11p and DMMAC for given scenarios

	Improvement of MAMBA over IEEE 802.11p	**Improvement of MAMBA over DMMAC**
Highway, high density	63.05%	98.43%
Highway, low density	46.91%	97.80%
Urban, high density	71.57%	98.80%
Urban, low density	60.60%	98.75%

The reason MAMBA performs better than IEEE 802.11p in terms of latency is because of the difference between contention-based approaches (IEEE 802.11p) and contention-free approaches (MAMBA). MAMBA guarantees timely access to the medium, while IEEE 802.11p suffers when the load is high, which is why the performance improvement is more pronounced in the high density scenarios. The small variation in latencies is also due to this latency guarantee with MAMBA.

DMMAC performs poorly in terms of latency because vehicles are unable to allocate slots because of saturated SATs. Nodes that have not successfully allocated slots in a TDMA network are not able to transmit until a slot is allocated. Consequently, packets accumulate at the MAC layer causing an increase in their transmission delays. One way to address the problem of ageing packets at the MAC layer would be to allow messages to expire, freeing up space for new messages. This approach would, however, lead to a lower delivery ratio. Simulation results obtained showed that an average of around 40% of packets (in all scenarios) with DMMAC would have expired at the MAC layer if a message expiration time of three seconds was set for the MAC layer. The other non-zero percentage (as shown Figure 15) was 0.3% for IEEE 802.11p in the urban high density scenario. A message was considered to be outdated after three seconds, in line with the stringent latency requirements evident in VANET safety requirements [43].

7. CONCLUSION

In this paper we presented an overview of concepts key to vehicular networking. We described in detail two categories of MAC approaches namely the contention-based IEEE 802.11p approach, which is also the existing standard, and the contention-based DMMAC approach. We highlighted some of the limitations of these approaches and proposed an improved MAC method, called MAMBA. We described in detail our simulation setup, which includes a network simulator, a road traffic simulator, and real-world maps, and we listed the simulation parameters and metrics used. Finally we compared the performance of our proposed MAC approach (MAMBA) with the performance of IEEE 802.11p and DMMAC approaches for various traffic scenarios. The simulation results obtained demonstrate significant performance improvements (in terms of throughput, message delivery ratio, and latency) with MAMBA over IEEE 802.11p and DMMAC.

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